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A FRAMEWORK FOR RESEARCH ON ADAPTIVE DECISION AIDS

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FOR THE COMMANDER

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Director, Human Engineering Division
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A review of the literature on decision aids is presented, with particular emphasis on aids that adapt to situations and/or users. A framework for design of adaptive decision aids is proposed and used to identify design issues associated with aids for command and control. This framework is also used as a basis for defining several important research issues that should be addressed if adaptive aiding technology is to progress.

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INTRODUCTION

Advances in computer and communications technology have enabled the development of increasingly complex systems. As a result, the humans involved in these systems are faced with substantial increases in the amount of information they must integrate into the decision making process and, in some cases, increasingly tight time constraints within which decisions must be made. With goals of ameliorating these problems, a variety of decision aids have been developed and tested. Unfortunately, few of the plethora of aids available have met any significant degree of operational success.

There are several possible explanations for this lack of success. One possibility is that the aiding methodologies employed have been inadequate. Another possibility is that the interface between user and aid limits success even if the underlying methodology is appropriate. Yet another potential explanation for aids not being accepted is that user participation in design has not been given the necessary primacy. Many authors have argued for improvements in these areas and a general awareness, if not solutions, of these problems is ubiquitous.

Another potential contributing factor is the inherent inflexibility of an aid that only provides static computational

and bookkeeping functions designed to support the average user in the average situation, when virtually all decision making involves a particular individual in a specific situation. What may be required for success is that aids adapt to individuals and situations, perhaps in a manner similar to that of human staff or crew members in the military and industry. It seems reasonable to argue that aids which could adapt in this manner are quite likely to overcome many of the user acceptance problems encountered in the past.

The purpose of this report is to present a framework for research on adaptive decision aids and to illustrate the use of this framework for recommending important and promising research directions within the area of command and control systems. The discussion begins with an overview of recent literature on decision aids, proceeds to presentation of the general framework, and concludes with consideration of implications for command and control.

THE LITERATURE

In order to assess the state of the art in decision aiding, an extensive literature review was performed. Emphasis was placed on the journal and conference publications of the IEEE Systems, Man, and Cybernetics Society as well as government contractor technical reports. These two sources produced 104 documents; 16 additional documents were obtained from other journals and conference proceedings. Thus, the discussion in this section is based on a survey of 120 documents. Considering the fact that many of these documents (i.e., 20) were in themselves reviews of the literature, the breadth of literature covered both directly and indirectly is substantial.

The literature which focuses on particular applications can be divided into three categories: 1) military, 2) nonmilitary, and 3) methodological. In the military category, 42 documents were reviewed in the following subcategories: Army tactical operations (12), Air Force/Navy aircraft operations (17), Navy marine operations (10), and other (3). The nonmilitary category included 36 documents in the following subcategories: aircraft operations (9), process control and manufacturing (8), management (7), design and analysis (6), and other (6). The methodological category included 14 documents in the subcategories of decision structuring (9) and extensions of decision analysis (5). Thus, the distribution of documents across applications areas is

reasonably broad.

Many of the documents discuss topics that are fairly general and go beyond any particular application. Six general topics that emerge are:

1. Reviews of human information processing, behavioral decision theory, aiding methodologies, available decision aids, and evaluation (20).

2. Attributes of situations, information, and decision making (13).

3. Disaggregations of decision making into various tasks, phases, stages, etc. (8).

4. Types and levels of decision aiding (14).

5. Aids that adapt, or can be adapted, to particular situations and/or individual decision makers (29).

6. Principles, guidelines, and/or processes for designing aids (16).

(The number in parentheses following each topic indicates the number of documents discussing that topic.)

Reviews

Considering the review literature, the topic most frequently addressed is human information processing. These reviews amass an impressive array of literature to support the overall

conclusion that human abilities are limited and individual differences are important. It is usually argued, quite reasonably, that human limitations should be considered when designing aids and, if possible, aids should adapt to individual differences.

Another popular topic in the review literature is the potential applicability to decision aiding of artificial intelligence or advanced software engineering methods. There appears to be a fairly clear consensus that traditional decision analytic methods (i.e., decision trees, multiattribute utility theory, etc.) must be augmented to achieve wider applicability and acceptance. This is particularly true in terms of initial problem structuring and generation of alternatives. In general, the rule-based or knowledge-based "expert" systems deal with the context of a problem more directly than possible with decision analytic methods.

Decision Making Tasks

A variety of authors have concerned themselves with classifying decision making situations, information requirements and systems, and decision making problems. The attributes of the resulting classification schemes tend to be either rather qualitative or fairly context-specific. All of these classification efforts represent attempts to partition the

decision aiding problem into more manageable subproblems. As will be seen, this approach has been adopted in this report for formulating the overall problem of adaptive decision aiding.

One aspect of this decomposition approach that deserves particular attention is the disaggregation of decision making into tasks, phases, stages, etc. While a wide variety of alternative decompositions have been discussed, the differences among these alternatives are mainly due to variations in terminology among contexts. It is fairly straightforward to synthesize the alternatives into a single set of decision making tasks such as the following:

1. Detection of problem
2. Acquisition of information
3. Evaluation of information
4. Integration of information
5. Generation of alternatives
6. Evaluation of alternatives
7. Selection among alternatives
8. Implementation of choice
9. Monitoring of consequences

The tasks in this list could be aggregated into decision making functions such as situation assessment (nos. 1, 2, 3, and 4), planning (nos. 5, 6, and 7), and control (nos. 8 and 9) or disaggregated into elements of human information processing such as perception, estimation, prediction, etc. The level of description which is most appropriate depends on the purpose of the description. A later section of this report pursues this issue further in the context of command and control systems.

Decision Aiding Possibilities

Considering the many documents which discuss the types and levels of decision aiding possible, the following is a reasonable integration of the numerous suggestions:

1. Alerting - recognizing that a particular situation now exists or warning that the situation is likely to arise
2. Acquisition - identifying information sources, selection among sources, and information retrieval and display
3. Evaluation - organizing and integrating information, performing calculations including predictions, and identifying model parameters
4. Synthesis - generating alternatives and explaining their origins, strengths, and weaknesses
5. Advising - monitoring and compensating for human errors and biases, explaining behavioral inconsistencies, and recommending courses of action.

Aids in the alerting category are so common in the vehicle and process control domains that one seldom thinks of them as

decision aids. Most current aiding systems provide support in the acquisition and evaluation categories, with management information systems typically focusing on the acquisition process while decision support systems usually emphasize evaluation.

Many of the more recent aiding concepts are oriented toward synthesis and advising. Expert systems usually are designed to generate and explain alternatives within some limited problem domain. These systems also typically provide advice. However, the static context-dominated nature of most current expert systems does not allow for the adaptation necessary to provide the full advisory function as defined above.

Design of Decision Aids

The literature on design processes deals with three levels of issue: 1) system design in general, 2) design of decision aids, and 3) steps of decision aiding. The nature of the literature is such that even the lowest level issues are expressed in very general terms. In this sense, design processes outline an ordered set of issues to be considered rather than specific procedures for design.

The principles and guidelines presented in the literature provide general desiderata and specific issues, respectively, to be considered in designing aids; however, unlike design

handbooks, they provide little direction regarding specific choices in addressing issues and resolving tradeoffs. Many of the principles and guidelines reflect issues relevant to human-machine interaction in general, while others focus specifically on the design of decision aids. As might be expected, the most definitive principles and guidelines are those that have been culled from the relatively large data base on human-machine interaction in general. Principles and guidelines specific to decision aiding tend to be rather broad and somewhat difficult to operationalize. This observation will be elaborated upon when design principles and guidelines are discussed in the next section in terms of a framework for adaptive decision aids.

ADAPTIVE DECISION AIDS

While quite a few documents are noted above as dealing with adaptive decision aids, almost all of these documents have been generated by two research groups: 1) Perceptronics, Inc. and 2) the authors' group while at the University of Illinois and, more recently, Georgia Institute of Technology. These two efforts are briefly reviewed in this section prior to introducing a general framework for adaptive aiding.

Background

The essence of Perceptronics' approach to adaptive aiding, at least initially, has been the use of multiattribute utility functions to represent decision makers' relative preferences among information sources, and the use of fairly straightforward pattern recognition techniques for adapting the parameters of the utility function to individual decision makers. This approach has been applied to computer-aided information selection via utility maximization in aircraft, antisubmarine warfare, and command and control environments. Recently, Perceptronics has integrated their basic approach with rule-based models and simulation to allow application of their adaptive aiding notions to a wider range of decision tasks.

The authors and their colleagues have pursued the problem of

adaptively (i.e., dynamically in time) allocating decision making tasks between humans and computers. Succinctly, the idea has been to use the computer to make the allocation decision (or recommendation) so as to minimize task delay time, subject perhaps to maintaining human workload at a satisfactory level. A queueing theoretic model was used to formulate this problem and provide the basis for the aiding algorithm which was tested in the aircraft domain.

The feasibility of this approach to task allocation depends on the resolution of several issues associated with human-computer communication. Via simulation studies, it was found that computer aiding would be most effective if the computer knew the human's current state of knowledge, current allocation of attention, and intended allocation of attention. Because of the cost (i.e., time and workload) of having the human overtly or explicitly communicate this type of information, covert or implicit approaches to communication were considered including direct but unobtrusive observation (e.g., eye tracking), inference via physiological measures, and inference via model matching. Model matching has been the approach which has received most attention with several models having been developed which worked quite well in laboratory evaluations.

The work of Perceptronics and that of the authors and their colleagues are examples of situations where the computer adapts

itself to the human. An alternative is to have the human adapt the computer to himself. Examples in the literature reviewed include user personalization of display formats, customization of interface features, and online modification of outputs of aiding algorithms. One of the tangible benefits of the user-initiated approach is that the human then clearly knows what adaptation has occurred. In contrast, if the computer automatically adapts to the user, it can prove difficult to supply the user with meaningful and easy-to-digest information regarding the status of the adaptive system (e.g., who has responsibility for which tasks).

While much of the research reviewed thus far in this section has addressed some of the central questions in adaptive aiding, this overall set of efforts has been far from comprehensive. What has been lacking is a framework within which to view the general topic of adaptive decision aids. The remainder of this section is devoted to proposing such a framework.

Overall Framework

Conceptual frameworks should be developed to serve particular purposes. In that sense, no useful framework is completely general. However, it is possible to generalize in the sense of serving a specific purpose across multiple problem domains. For this report, the goal is to suggest a framework

that outlines the research issues in adaptive aiding in a manner that is relevant to vehicle and process systems, command and control, management systems, etc.

The overall structure of the proposed framework involves the following six attributes of an adaptive decision aid:

1. Type of decision task
2. Level of decision aiding
3. Form of adaptation
4. Mode of adaptation
5. Method of adaptation
6. Means of communication

The first two attributes (i.e., type of task and level of aiding) were discussed in the previous section and need little further elaboration at this point except perhaps to point out that resolution of the issues associated with the other four attributes (i.e., form, mode, method, and means) is often likely to depend on the type of task and level of aiding.

Form of Adaptation

The *form* of adaptation relates to the question: *what is*

adapted to? This question can be answered at several levels. At the highest level, adaptation can be relative to the task or user. At the lower levels of detail, adaptation can involve a class of tasks or users, a particular member of a class, or the state of a particular member. For example, an aid might adapt to the class of all impulsive or field dependent decision makers, or to a particular decision maker who exibits some specific degree of membership in the class, or to a decision maker in a particular state at a specific time (e.g., high workload two minutes prior to touchdown).

Therefore, adaptation can be relative to the task or user and, within these categories, relative to a class, member, or state. Virtually any design is adapted (albeit offline by the designer) to a class of tasks or users. Thus, the key distinction here is between adapting to members (e.g., particular users) versus states (e.g., specific situations at particular points in time).

Mode of Adaptation

The mode of adaptation concerns the question: who does the adapting? There are three possible answers to this question: 1) designer, 2) user, and 3) the aid itself. A further aspect of the mode of adaptation is whether it is done offline or online. Any adaptation by the designer is, by definition, performed

offline while users and aids usually adapt online. However, it is easy to envision users, for example, personalizing display formats and customizing interface features in an offline mode. Of course, in this mode, the distinction between designer and user becomes fuzzy unless one specifies that designers' adaptations are, by definition, always for other than themselves.

Designer-offline adaptation typically involves classes of tasks and users. This combination of the attributes of "form" and "mode" is practically identical to how one might characterize the design of nonadaptive aids. From this perspective, one can view more traditional decision aids as special cases of adaptive aids where all adaptation is done offline by a designer who attempts to anticipate task and user characteristics.

Method of Adaptation

The method of adaptation relates to the question: how is the adaptation done? In general, adaptation involves measurements which are manipulated using models such that modification of various types may result. A continuum of modification is possible. The highest level modification is the allocation of tasks (e.g., who does the information selection). A lower level modification involves partitioning of a task (e.g., human chooses setpoints and computer controls relative to this reference). The lowest level modification involves

transformation of a task (e.g., abstracting a display from a physical to a functional representation).

The range of measurements and models involved with these levels of modification can be rather large. The particular choices among alternative measures and models are dictated by the level of modification desired as well as the form and mode of adaptation, with of course consideration given to technical feasibility and reliability. Typically, measures are difficult to obtain, while there are a plethora of reasonable models, among which the choice is highly influenced by the modeler's experiences and preferences.

Alternative types of measurement include task variables (e.g., the state of the system), user variables (e.g., workload), user task-related responses (e.g., usage of commands), and user adaptation-related specifications (e.g., format and dialogue preferences). Types of model can range from quantitative computational models that allow prediction of overall performance (e.g., manual control models), to models that predict particular choices (e.g., decision theoretic models), to qualitative models that are concerned with predicting modes of behavior (e.g., pattern recognition vs. structural search) instead of particular responses.

Means of Communication

The means of communication refers to the manner in which measurements are made and the way in which users and aids inform each other of the status of the decision making process. As noted earlier in this section, communication can be either explicit (overt) or implicit (covert). Explicit communication may involve specific displays and controls, structured dialogues via keyboards or voice, or natural language via keyboards or voice. Implicit communication can be accomplished using unobtrusive but direct observations, indirect measurements, or inference.

The distinction between explicit and implicit communication relates to the user's awareness of the communication. Therefore, explicit communication is such that the user is aware that he or she is communicating with the aid. In contrast, implicit communication is such that the user will only be aware of doing the task; the user is not consciously aware of the fact that the aid is gleaning information from these task-related activities.

The differentiation of direct, indirect, and inferred measures is made to emphasize the degree to which measurements may have to be transformed and interpreted. A direct measurement of, for example, aircraft altitude and attitude or a user's choice between modes of operation requires no transformation or interpretation; the measurement directly supplies the

information sought. Indirect measurements require transformations (e.g., via deductive principles of physical or behavioral science) in order to obtain the desired information. Inferred measurements require interpretation (e.g., induction via models), perhaps to the extent that one must extrapolate to obtain the information of interest.

Summary and Example

Figure 1 summarizes the form, mode, method, and means attributes of adaptive decision aids. These attributes typically interact with the type of task and level of aiding attributes. However, to streamline the presentation, these two attributes are not indicated in this figure.

Considering the various types of task, levels of aiding, forms, modes, methods, and means in Figure 1, there would appear to be thousands of potential adaptive aids. However, the apparent uniformity and completeness of the classifications shown in this figure mainly serve to clarify the presentation; many of the combinations indicated are neither interesting nor meaningful. (See notes on Figure.) This is due to the fact that the purpose of this figure is not enumeration of all possible aids; instead its purpose is to clearly summarize the issues to be addressed, questions to be answered, and the nature of possible answers. The usefulness of such a framework is illustrated in the next section by focusing on command and control systems.

FORM OF ADAPTATION: WHAT IS ADAPTED TO?

	CLASS	MEMBER	STATE
USER	1	2	2
TASK	1	2	2

MODE OF ADAPTATION: WHO DOES THE ADAPTING?

	DESIGNER	USER	AID
OFFLINE	1	2	3
ONLINE	4	3	2

METHOD OF ADAPTATION: HOW IS THE ADAPTATION DONE?

	ALLOCATING	PARTITIONING	TRANSFORMATION
MEASUREMENTS	2	2	2
MODELS	2	2	2

MEANS OF COMMUNICATION: HOW IS INFORMATION TRANSMITTED?

	DIRECT	INDIRECT	INFERRED
EXPLICIT	2	3	3
IMPLICIT	3	2	2

Notes:

1 = always combined
2 = frequently combined
3 = seldom combined
4 = never combined

Figure 1. Four Attributes of Adaptive Decision Aids

However, rather than immediately consider a domain as complex as command and control, the use of the framework summarized in Figure 1 can be illustrated with a more straightforward example. Consider the task of computer-aided pattern recognition where the patterns of interest are such that human abilities surpass those of the computer unless the time pressure on the human becomes excessive; then, the computer's abilities are better and acceptable. The design problem is to develop a mechanism for determining who (human or computer) should perform the task at any point in time.

The degradation of human pattern recognition abilities with increasing time pressure is likely to depend on the complexity of the patterns being viewed. Recognition performance for simple patterns (in simple backgrounds) is likely to be maintained for all but extreme levels of time pressure. However, for complex patterns (in complex backgrounds), recognition performance is likely to be quite sensitive to time pressure. Therefore, it is probably reasonable to allocate the recognition task on the basis of both pattern complexity and time pressure.

Figure 1 can be used as a basis for exploring alternative approaches to this design problem. Considering the form of adaptation (i.e., what is adapted to?), any viable aid would have to be designed to at least be consistent with a class of patterns (e.g., aerial reconnaissance) and a class of users (e.g.,

aircraft pilots). As noted earlier, this would represent a baseline nonadaptive aid.

If the aiding mechanism was adapted (e.g., via threshold parameters) relative to particular types of pattern (e.g., enemy tanks in wooded background) and/or specific levels of time pressure (e.g., nap-of-the-earth flight at a given speed), then the form of adaptation would be "task-member." If pattern or background characteristics, or time pressure parameters, were measured and updated online with subsequent adaptations of the aiding mechanism, the form would be "task-state." Considering the user, if an individual's score on a pattern recognition test (e.g., the embedded figures test) were used to adapt aiding parameters, the form would be "user-member." Finally, if adaptation were on the basis of an online measurement of mental workload, the form of adaptation would be "user-state." From this example, it should be clear that a particular aid can embody more than one form of adaptation (e.g., "task-member" and "user-state").

With regard to the mode of adaptation (i.e., who does the adapting?), the baseline nonadaptive aid would be such that the designer would adjust the aiding mechanism offline to "task-class" and "user-class." If the aid adapted its mechanism prior to task performance relative to expected pattern and background characteristics, as well as the anticipated level of

time pressure, the mode of adaptation would be "aid-offline." If these variables were assessed and adapted to online by the aid, the mode would obviously be "aid-online." If the user adapted the parameters of the aiding mechanism relative to these variables prior to or during task performance, the mode would be "user-offline" or "user-online," respectively.

Considering the <u>method of adaptation</u> (i.e., how is the adaptation done?), the pattern recognition task could be allocated to either human or computer. Alternatively, the task could be partitioned into subtasks (e.g., human identifies feasible set, computer evaluates degree of match of each candidate, and human chooses among evaluated alternatives). Aided transformation might involve smoothing, rotating, or inverting the displayed patterns.

The choice among these types of modification would depend on the task characteristics of pattern complexity and level of time pressure as well as user characteristics such as individual pattern recognition abilities, resilience to time pressure, and perhaps current workload. Some of these variables could be measured directly; others could be deduced from indirect measurements; and some could be inferred using models of human performance. These measurements would serve as inputs to a model that would predict the most appropriate level of modification (i.e., allocated, partitioned, or transformed). This model might

be simply a look-up table of precomputed aiding parameters as a function of task and user variables. Or, the model might be more computational in manner, perhaps updating deductions and inferences as measurements change.

With regard to the <u>means of communication</u> (i.e., how is information transmitted?), any direct communications would depend on explcit user involvement. For example, the user might specify pattern complexity. However, indirect and inferred communications are more likely. An example of indirect communication would be the transformation of altitude and airspeed into an estimated viewing time for target patterns. If the user specifies altitude and airspeed, the means would be "explicit-indirect;" if the measurement and transformation proceeds without user involvement, the means would be "implicit-indirect." Another example of indirect communication would be user specification of his ID number which would enable access to a data base of characteristics for the particular user. Since the user is likely to be aware of why he is supplying the ID number, the means would be "explicit-indirect."

Inferred communications are usually implicit, unless the aid explicitly communicates with the user to confirm its inferences. An example of model-based inference would be the use of performance on a concurrent task (e.g., rms control activity) and an indirect assessment of time pressure (e.g., via altitude and

airspeed) as inputs to a model that would enable one to infer the level of complexity of target patterns. For a task such as time-pressured pattern recognition, it is likely that most communications involving measurements of variables would be "implicit-indirect" or "implicit-inferred."

Another aspect of communication involves feedback to the user regarding the current level of modification. If the modification involves allocation, communication obviously must be "explicit-direct." A modification involving partitioning would probably be "explicit-direct," although one can imagine situations where the user would only be implicitly aware that the aid was performing an unseen portion of the task. Transformation is a type of modification that might very well be communicated implicitly and perhaps involve indirect measurements or inference on the part of the user.

This brief example has illustrated how the framework summarized in Figure 1 can be used to pose design questions and the nature of answers. While it is very difficult, if not impossible, to enumerate alternative answers to each type of question (particularly for measurements and models), the framework helps the designer to consider systematically the range of issues of importance. The following section pursues this approach for identifying adaptive aiding issues in command and control.

IMPLICATIONS FOR COMMAND AND CONTROL

Several documents (i.e., 8) provide overviews of command and control within particular military domains. The functions or missions discussed include: 1) aircraft operations; interdiction, close air support, interception, reconnaissance, defense suppression, and air lift, 2) naval operations; antisubmarine, antisurface, and antiairwarfare, and 3) other; amphibious assault and surface-to-surface missile warfare. This great variety of functions makes it very difficult to formulate a general framework for command and control. However, if one considers the decision making tasks involved in accomplishing these functions, a fairly general structure emerges.

Figure 2 is a synthesis of the various views of command and control decision making expressed in the literature reviewed.* This figure is basically an elaboration of earlier discussions in this report, with emphasis on common attributes of tasks as well as relationships among tasks. The first portions of this section discuss the nature of the tasks depicted in Figure 2. Following this discussion, possible aids for these tasks are considered.

*It should be emphasized that this synthesis is based almost totally on the authors' previous efforts in decision making research as well as conceptual frameworks proposed by other authors. It is interesting to note how a number of researchers have all advocated basically the same conceptualization, but with different terminology. Certainly the synthesis presented here is, in essence, another variation of this standard theme.

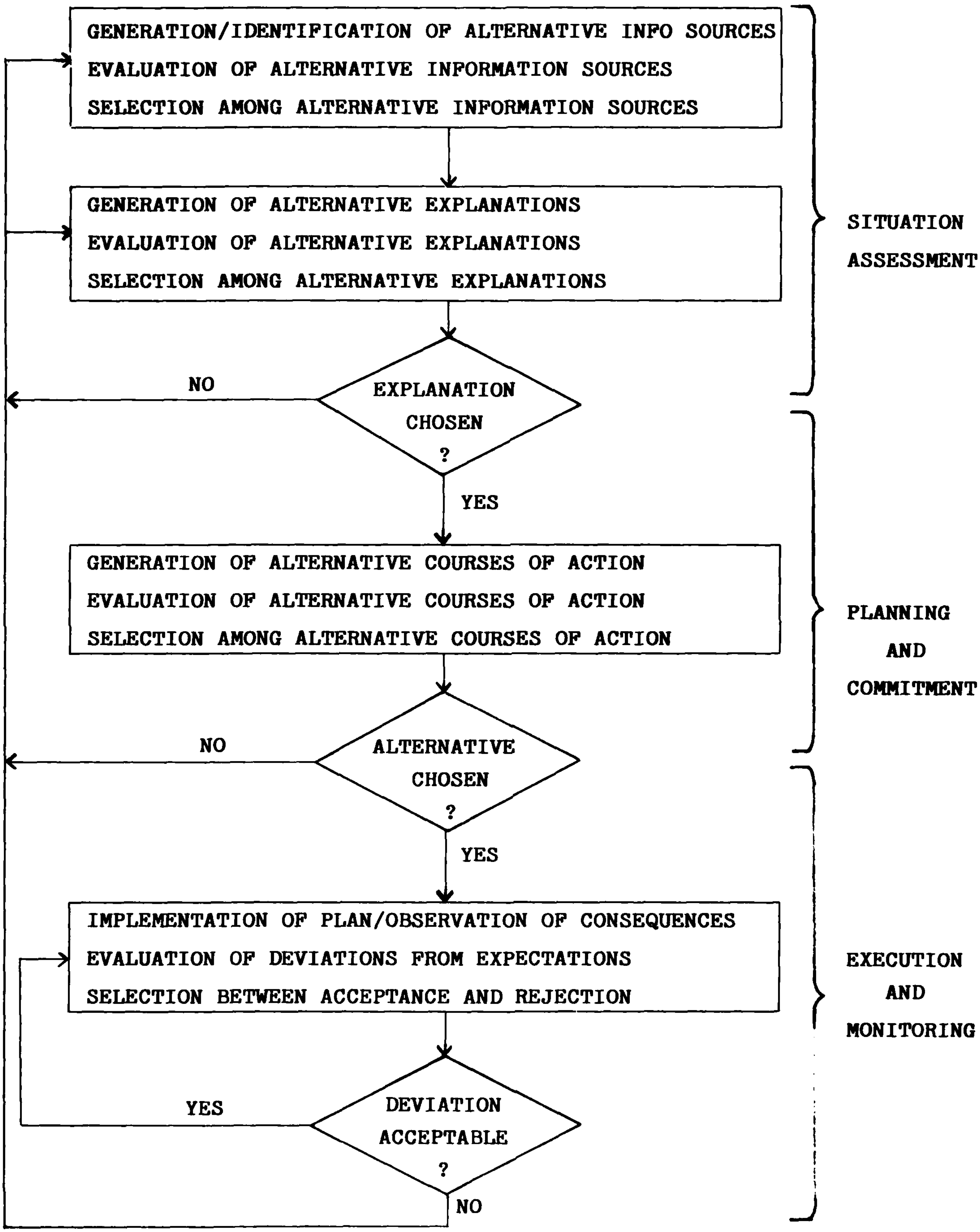

Figure 2. Command and Control Decision Making Tasks

Situation Assessment: Information Seeking

Situation assessment can be viewed as involving two phases: information seeking and explanation. Information seeking includes generating/identifying, evaluating, and selecting among alternative information sources. The alternative information sources are usually fairly well defined in command and control. They include data bases, sensors, and models which can be viewed as providing information about what has happened (past), is happening (present), and may happen (future), respectively.

Generation/identification of alternative information sources involves rapidly (and perhaps unconsciously) considering the large number of information sources available and delimiting a reasonable subset for further consideration. Evaluation of information sources involves assessing their relevance, information content, and resource requirements.

Selection among alternative information sources basically involves the allocation of information acquisition resources (e.g., people, sensors, and bandwidth) relative to criteria such as uncertainty reduction and resource constraints. Given the outputs of the evaluation task and clear statements of the allocation criteria, selection in terms of resource allocation can be posed as a rather standard optimization problem. However, humans do not appear to approach selection quite so rigorously

which may provide opportunities for aiding as is discussed later.

Situation Assessment: Explanation

The explanation phase of situation assessment includes generating, evaluating, and selecting among alternative explanations of the situation. Generating alternatives involves synthesizing possible explanations of what has happened, is happening, and may happen. Typically, there is a default explanation which concludes that a priori expectations have been, are, or will be fulfilled. The process whereby other alternatives emerge appears to depend on previous experiences, pattern recognition abilities, and perhaps creativity.

Evaluation of alternatives involves finding the degree of correspondence between each candidate explanation and the assessed situation. Beyond assessing the degree of fit, evaluation also includes determining the cost of both types of misevaluation (i.e., false acceptance and rejection of alternatives). In general, the cost of falsely accepting an alternative depends on the particular alternative that is consequently falsely rejected. In ambiguous situations where many alternative explanations are feasible, the interdependencies of these costs of error can be complicated to keep in mind and would seem to be a possible area for computer aiding.

Selection among alternatives involves trading off the feasible explanations in terms of the degree of correspondence with the assessed situation and the costs of false acceptance and rejection. If the values of all of the parameters associated with these tradeoffs were known, selection could be viewed as a minimum expected cost optimization problem. However, it is very unlikely that humans make selections this formally, partially because of inherent ambiguities in situations and explanations, and partially due to human information processing limitations. Therefore, as with selection among information sources, selection among explanations may be an appropriate task for aiding.

Planning and Commitment

Planning and commitment includes generating, evaluating, and selecting among alternative courses of action. Planning differs from situation assessment primarily in terms of being purely future-oriented and emphasizing a sequence of actions over time rather than an assessment at a particular point in time. Thus, while situation assessment attempts to determine what has happened, is happening, or may happen, planning focuses on manipulating future situations by choosing appropriate courses of action.

Generating alternative courses of action is similar to generating alternative explanations. Typically, courses of action that have been successfully used before in the given

situation will be considered. Often, such courses of action or plans may be available in the form of procedures. Alternative plans also may emerge from experiences with analogous situations or, if absolutely necessary, via analytical study of the situation. It is difficult to say where truly novel alternatives come from; while this makes alternative generation a difficult process to aid, it nevertheless does support a design principle requiring sufficient system flexibility to avoid inhibiting creativity when it is needed.

Evaluation of alternative courses of action involves assessing or imagining the consequences of plans, both in terms of impact on future situations and resource requirements. This type of evaluation is usually performed by mapping (correctly or otherwise) from possible actions to previously experienced consequences. In many situations, training will enable reasonably accurate anticipation of effects of actions. When costs of forecasting errors are high and time allows, evaluation of alternative actions may be performed using predictive models, perhaps the simplest operational form of which is a predictor display.

Selection among alternative courses of action involves the allocation of action resources (e.g., people and equipment) relative to criteria which assess the degree to which objectives are achieved over some planning horizon, and subject to resource

constraints. As with the other types of selection task, given sufficient information, selection among alternative courses of action can be posed as a constrained optimization problem. However, the complexity of such a formulation dictates that unaided humans are very unlikely to pursue selection in this manner. While aiding may be possible, its feasibility is likely to depend totally on the availability of types of information which humans may have difficulty assessing and/or communicating.

Execution and Monitoring

Execution and monitoring include implementing the plan selected, observing its consequences, evaluating deviations of observed consequences from expectations, and selecting between accepting and rejecting deviations as being within the range of possibilities given chance variations in consequences. Plan implementation involves control in the sense of communicating and manipulating, and coordination in terms of sequencing and balancing the deployment of resources. Observation of consequences involves acquiring information and correlating it with the course of action implemented.

Evaluation of deviations of observed consequences from expectations is the process of determining whether or not the actual course of events significantly deviates from what was anticipated to be the result of plan implementation. While some deviations are quite normal, excessive deviations indicate that

something is awry (e.g., the situation assessment may have been wrong). Obviously, the quantitative definition of "excessive" depends on the uncertainty associated with a priori expectations of consequences.

Selection between acceptance and rejection of the observed deviations as normal involves trading off the costs of false acceptance or rejection in terms of the costs of incorrectly proceeding with execution and the costs of wrongly abandoning execution to return to situation assessment and/or planning. Given sufficient information, this decision task can be viewed as simply one of choosing the minimum expected cost alternative. However, since probabilities and costs of selection errors are usually not explicit, this selection task, as with the selection tasks discussed earlier, is not so straightforward.

Input/Output

The terms used in Figure 2 and the above discussion were designed to emphasize common attributes of decision making tasks in command and control. Clearly, the three most central words in this formulation are generation, evaluation, and selection relative to alternative information sources, explanations, courses of action, and deviations from expectations. Beyond these types of decision, there are input and output tasks that are common to all of the decision making tasks. Since the same information displays, input devices, and dialogue structure can

support different decision making tasks, albeit perhaps in different ways, these input/output tasks are not shown in Figure 2. Therefore, for example, the act of obtaining information from displays is not viewed as a separate decision making task per se.

Nevertheless, these input/output activities are good candidates for aiding in order to free humans to attend to generation, evaluation, and selection. For example, acquisition and integration of information is an area where aiding can be quite useful. Acquisition and integration of information involves querying data bases, sensors, and models, and integrating the information produced into a coherent picture. The acquisition process is fairly straightforward if controls and displays are reasonably designed. Integration is more subtle in that it usually relies on humans' impressive pattern recognition abilities. These abilities can be exploited by appropriate transformation, formatting, and coding of information to match individual differences as well as population stereotypes.

Opportunities for Aiding

The discussion has now progressed to the point that aiding can be considered in terms of five generic tasks: generation, evaluation, selection, input, and output. From a human information processing point of view, these five tasks represent three types of processing: 1) input or perceptual processing, 2) central or cognitive processing (i.e., generation, evaluation,

and selection), and 3) output processing. Thus, these tasks and the alternative aiding concepts discussed in this and the following subsection cover the full range of human information processing.

In order to suggest potential aids, assumptions must be made regarding the availability of information to the aid. There are basically three sources of information. The most obvious is measurements which are, for example, the typical approach for assessing system state variables, (i.e., velocities, altitudes, temperatures, pressures, etc.). A second source of information is user specifications where, for instance, the user might specify final decisions regarding the situation assessed, explanation accepted, or plan chosen. The third source of information is inferences based on measurements and specifications.

In the following discussion, the phrase "For a given...," is frequently used. The word "given" is defined here as the product of accessing information via direct or indirect measurements, user specifications, and/or inferences. Thus, the word "given" is used here to state the a priori knowledge an aid is assumed to have.

Aids for generation are among the most difficult to imagine since generation can be a rather creative activity. However,

while creativity may be difficult to replace, it can be supported. The following levels of aiding seem feasible:

1. For a given situation, an aid might retrieve previously relevant and useful alternatives.

2. For a given set of attributes, an aid might retrieve candidate alternatives with these attributes.

3. Given feedback with regard to suggested alternatives, an aid might adapt its search strategy and/or tactics.

Aids for evaluation are among the more straightforward. To a great extent, such aids are basically information retrieval and calculation routines. While the human factors issues associated with specifying and displaying this information are by no means trivial, these issues are related to input and output rather than evaluation. Possible types of aiding for evaluation include:

1. For a given alternative, an aid might assess the alternative's a priori characteristics such as relevance, information content, and resource requirements.

2. For a given situation and alternative, an aid might assess the degree of correspondence between situation and alternative.

3. For a given alternative, an aid might assess the likely future consequences such as expected impact and resource requirements if the alternative is chosen.

4. For given multiple alternatives, an aid might assess the merits of each alternative relative to the other alternatives.

5. Given feedback of appropriate variables, an aid might adapt its evaluations in terms of time horizon, accuracy, etc.

As noted in earlier discussions, selection can be posed as an optimal resource allocation problem if sufficient information is available. While information is often lacking, efficient methods (i.e., minimum number of questions) of querying the decision maker have recently been developed and would seem to offer a means of ameliorating this difficulty. Potential types of aiding for selection include:

1. For given criteria and set of evaluated alternatives, an aid might suggest the selection that yields the best (e.g., minimum cost) allocation of information acquisition and/or action resources relative to given resource constraints and planning horizon.

2. For given individual differences and time-variations of criteria, preferences, and evaluations, an aid might adapt its suggestions to reflect these variations.

Input tasks are concerned with acquisition and integration of information as well as observation of consequences. Aids for input tasks basically involve the way in which information is shown to the user. Possible aids include:

1. For given information, an aid might transform, format, and code the information to avoid human limitations and exploit human capabilities.

2. For a given set of evaluated information, an aid might filter and/or highlight the information to emphasize the most salient aspects of the information.

3. For a given sample of information, an aid might fit models to the information in order to integrate and interpolate within the sample.

4. For given constraints (e.g., time) and individual differences, an aid might adapt transformations, models, etc. accordingly.

Output tasks are those associated with plan implementation. While such tasks are not usually classified as decision making, aiding of implementation can be a very important aspect of a decision support system. The following levels of aiding appear feasible:

1. For a given plan and information regarding the user's actions, an aid might monitor implementation for inconsistencies and errors of omission and comission.

2. For a given plan and information regarding the user's actions, an aid might perform some or all of the implementation to compensate for the user's inconsistencies, errors, or lack of resources (e.g., time).

3. Given information on workload, urgency, etc., an aid might adapt its monitoring and/or implementation accordingly.

The various opportunities for aiding discussed above are not necessarily all of the possibilities. However, they are representative of what has been tried or at least suggested in the literature. Given these alternatives, the next topic of discussion is the possibilities for adaptive aiding.

Possibilities for Adaptive Aiding

Starting with the above outline of aiding opportunities, the framework for adaptive aiding introduced earlier can be used to define and explore the issues associated with adaptive aids. As noted earlier, the main purpose of this framework is to provide a structured set of questions, as well as possible categories of answers, that should be addressed when designing adaptive aids. From this perspective, it is quite unnecessary to attempt to provide entries for each element of each tabulation in Figure 1. Instead, as is illustrated in this section, Figure 1 should be used to motivate and organize exploration of relevant issues.

To illustrate this process, adaptive aids for generation of alternatives are first considered. The initial question in Figure 1 is: "What is adapted to?" An appropriate answer to this question is that the aid for retrieving alternatives might adapt its search strategy to the situation, desired attributes of alternatives, and/or user feedback in the sense of judgements of the relevance of initially retrieved alternatives. Using the terminology in Figure 1, these three types of adaptation involve members and states of the task dimension and states of the user dimension, respectively.

The second question in Figure 1 is: "Who does the adapting?" A partial answer to this question involves defining

who determines the situation, attributes, or feedback. Either the user must specify this information (perhaps indirectly) or the aid has to infer it. The remainder of this question relates to who adapts the search strategy. This may be accomplished either by the user specifying adaptations or by the aid performing the adaptation. Thus, the overall answer to this second question can range from solely the user, to a combination of user and aid, to solely the aid.

The third question in Figure 1 is: "How is the adaptation done?" Considering the "modifications" involved, the answer to this question depends on whether decision making responsibility is allocated to the aid or partitioned between the user and aid. For "allocation", the aid would infer the situation or attributes and then, adapt the search keys and/or logic and finally, suggest alternatives to the user. For "partitioning", the user would specify the situation, attributes, or feedback and the aid would adapt search keys and/or logic to produce suggested alternatives.

The "models" that would be needed to perform the adaptation would potentially include models to infer situations or attributes, models to determine appropriate search keys and/or logic, and models to interpret user feedback regarding initially suggested alternatives. The "measurements" involved would be task variables, user choices, and user specifications. Choices and specifications are differentiated here to contrast users'

decisions in the course of pursuing a task and users' direct communications with an aid.

The final question in Figure 1 is: "How is information transmitted?" Communications are classified as direct, indirect, and inferred along one dimension, and explicit or implicit along the other dimension. Direct communications include measurements of task variables, specifications by users, and information displayed to users. Indirect communications include users' decisions (e.g., commands employed or usage of suggested alternatives) that can be interpreted by the aid as communication of information. Inferred communications would include inferences of situations or attributes based on direct or indirect communications.

Typically, direct communications are explicit while indirect and inferred communications are implicit although, if the situation allows, some aspects of indirect and inferred communications may be made explicit to the user. This can be quite important if the user must detect and diagnose errors on the part of the aid.

One of the issues raised in Figure 1 that remains to be addressed is the extent to which adaptations are performed online or offline, and the degree to which the aid is "pre-adapted" via, for example, look-up tables of situations/attributes vs. search

strategies. The extent of such offline adaptation is highly dependent on the time constraints imposed by the particular environment. As a result, while the decision tasks depicted in Figure 2 represent command and control in general, the feasible forms, modes, methods, and means of adaptation depend on the time constraints operable in the command and control function of interest. Basically, loose time constraints allow for substantial online user-aid interaction and tight time constraints require much more autonomy on the part of the aid.

As another illustration of the use of the framework proposed in this report, consider adaptive aids for selection among alternatives. Relative to the question of "What is adapted to?", a task-oriented answer would include the set of alternatives and selection criteria as well as time-variations of alternatives and criteria. A user-oriented answer to this question would include individual differences (e.g., level of training) and individual preferences (e.g., attitude toward risk). Considering "Who does the adapting?", either the user must specify or the aid must assess variations of alternatives and criteria as well as relevant individual differences and preferences. Given this information, either the user or aid could perform the selection, although aided selection is certainly the norm in most decision support systems.

Relative to "How is the adaptation done?", modifications

could involve allocation or partitioning. For allocation, the aid would measure or infer variations and differences, and subsequently adapt the structure and/or parameters of the selection process. For partitioning, the user would specify variations and/or differences and the aid would adapt accordingly. The models of interest would be those needed for inferring variations and differences as well as models for multicriteria allocation problems. Considering "How is the information transmitted?", the nature of the answer would be similar to that for generation tasks.

As a final illustration of the use of the proposed framework, adaptive aids for output can be considered. Relative to "What is adapted to?", the answer is the plan to be implemented and time-variations of plan parameters. Considering "Who does the adapting?", either the user specifies the plan or the aid determines it via, for example, a data base of procedures or "scripts". The aid would then monitor plan execution and provide some form of feedback relative to inconsistencies and errors. When appropriate, the aid would assist by performing some or all of the plan implementation.

The questions of "How is the adaptation done?" suggests modifications in terms of allocating both monitoring and implementation to the aid or, alternatively, partitioning the task so that the human monitors and requests assistance whereupon

the aid performs the portion of the task delegated. The models needed here would be those associated with inferring intentions (i.e., plans), determining expectations and comparing them with observations, and relating workload, urgency, etc. to the possibility of achieving task objectives. Considering "How is the information transmitted?", direct communications would include task variables, user specifications, and displayed information. Indirect communications would include user decisions and assessments of variables such as workload. Inferred communications would include inferences of intentions (e.g., procedure in use) and requirements for assistance (e.g., excessive workload).

While it is not possible, within the scope of this report, to elaborate upon all of the aiding issues outlined in Figure 1 as they relate to the command and control decision making tasks in Figure 2, the above discussion should provide a clear indication of how this mapping is done and the way in which this framework identifies important issues in the design of decision aids. In the concluding section of this report, recommendations for research that have emerged from considering command and control within this framework are presented.

Design Principles and Guidelines

As noted earlier, a number of authors have proposed principles and/or guidelines for the design of decision aids.

Almost all of this material relates to basic human factors and human-computer interaction in general. Surprisingly little focuses on decision aiding per se. Of those authors who do consider the unique aspects of decision making that should influence design, most discussions are limited to recommendations of tasks that should be aided. Some discussion is devoted to when aiding is needed (e.g., during peak workload periods and in multitask situations). There is also a fairly standard litany regarding the need for aids to be adapted to specific situations, individual differences, and individual preferences.

Unfortunately, very few documents provide principles and/or guidelines for <u>how</u> to accomplish the design of aids. The following is a fairly complete list of principles and guidelines that relate specifically to decision making, particularly in terms of the tasks shown in Figure 2.

1. The operating principles of an aid should be sufficiently simple for users to understand them.

2. The structure of the aiding (e.g., data base and decision process) should be consistent with human cognitive organization.

3. The modes of failure of an aid should be detectable and understandable by users.

4. Aids should be easily updated and modified without compromising system integrity or users' understanding of their operations.

5. Aids' queries to users and information displayed should be

such that the impacts of decision making biases are minimized.

6. Recommendations produced by aids should include a range of alternatives and not just the theoretical optimum.

7. Aids should be able to explain the basis of their recommendations.

8. Aids should be such that users still feel involved in the decision making process.

Obviously, this list is very general and it is not necessarily straightforward to translate these principles and guidelines into the design of a specific aid. While it might seem that this translation problem mainly reflects an inadequate knowledge base, an equally important source of this difficulty appears to be a fairly poor communication process between basic research in human decision making and the design and implementation of decision aids. In general, it seems that the state of the art in understanding human decision making is much more advanced than reflected by available design principles and guidelines.

RECOMMENDATIONS AND CONCLUSIONS

The framework for research on adaptive decision aids proposed in this report has served to identify a wide variety of issues that should be addressed in the design and development of aids. While this framework may cause the reader to feel that design and development is rather straightforward, at least conceptually, this is really not the case since many of the questions raised cannot, as yet, be answered in operationally useful manners. In this concluding section, four areas are discussed where research is needed in order to provide the requisite answers.

User Specification of Information

Throughout the earlier sections of this report, the possibility of having users explicitly provide information to aids was noted. It was suggested that users could specify situations, attributes of alternatives, individual preferences, and so on. The obvious difficulty with this approach is the demands that it places on the user, demands that potentially could exceed the benefits provided by an aid. Nevertheless, there are some types of information for which humans are the best source, particularly because of human knowledge and pattern recognition abilities.

Given this situation, there is a need to develop more

efficient and effective methods for users to specify information required by aids in order to adapt. There appear to be three ways in which to deal with this problem. First, some information can be specified in advance, perhaps in the form of contingency tables. Second, methods can be developed for identifying preference structures, for example, in the minimum number of queries to the user. Third, various coding methods can be used to enable the user to communicate in the minimum number of symbols.

While all three of these approaches have received attention and progress is being made, the potential for user specification of all information required by aids is definitely limited. This is particularly true when time constraints are tight. Then, it is likely that aids will have to infer information in order to be useful.

Methods of Online Inference

Methods are needed whereby an aid can employ a knowledge base, as well as time histories of task variables and user decisions, to infer the requisite information. The inferences of interest encompass the situation, attributes of alternatives, information requirements, intentions or plans, individual differences, individual preferences, and variations in time of each of these types of information.

While this may appear to be a "tall order," two factors make online inference more tractable. First, and foremost, many command and control domains are heavily context-dominated. Therefore, the task structure is fairly well-defined as is the information that is relevant to different phases of task. Further, the training and, to at least a slight degree, the preferences of users are often doctrinally defined.

The second factor of interest is developments in advanced software engineering (i.e., artificial intelligence) where concepts such as "frames," "scripts," and "demons" are being put to practical use. Further, as noted earlier, the "expert system" idea is being incorporated in various decision support systems. Thus, the problem context seems sufficiently well-defined and the software tools appear available for developing methods of online inference. Of course, this is not meant to imply that such methods are totally straightforward. However, there is a technology base to support the needed research efforts.

Methods of Online Adaptation

Given that an aid can obtain all of the requisite information, either by user specification or by inference, methods of adaptation become the central issue. From the analysis outlined in earlier sections of this report, it appears to the authors that four topics deserve particular attention. The first involves the adaptation of computer-based search strategies to situations, attributes, etc. For example, a method

is needed for adapting search keys and/or logic to time-variations in attributes of desirable alternatives.

A second topic of interest involves adapting the structure and parameters of allocation algorithms so that aided selection can reflect individual preferences, time-variations of resource constraints, and so on. This topic is the most straightforward of those suggested here; it is included because of the ubiquity of selection aids.

A third topic for research is methods of adapting display transformations, formats, etc. to particular situations and individuals. While a notable amount of research has been directed at the appropriateness of different displays to various situations and types of individual, the results of this work have seldom been incorporated in online adaptive aids and subsequently experimentally evaluated.

The fourth and final topic recommended for research involves methods of adapting the level of aiding (i.e., monitoring vs. tranforming vs. partitioning vs. allocating) to time-variations of tasks as a function of individual differences and preferences. Conceptually, this idea is reasonably well-defined. However, due to the relative novelty of this idea, the research base needed to support the design of adaptive mechanisms is currently inadequate.

A Few Crucial Issues

There are a few issues that should heavily influence the way in which the research topics oulined above are pursued. Among these, perhaps the most important issue involves the degree to which there should be explicit communication between the user and aid. At one extreme, the aid could inform the user of everything that it infers and the resulting adaptations. At the other extreme, the aid could silently toil away with the user hardly aware that the task is being adaptively manipulated to improve performance. While one can easily envision potential advantages and disadvantages of either of these extremes, there is little empirical evidence to support such conjectures directly. Research is needed in which the degree of explicit communication is systematically manipulated, perhaps in conjunction with individual differences and preferences.

Another crucial issue involves development and testing of online methods for assessing workload, attention allocation, planning activity, task urgency, and other important information to be used in adapting aids. Measurement techniques in these areas would reduce the need for inference of requisite information, which is likely to improve accuracy and simplify software. While a variety of measurement methods in these areas has been reported in the literature, few of the methods have been assessed in an online aiding environment. A comprehensive survey

and selected testing are needed.

Finally, the resolution of all of the issues discussed in this report is very dependent on the time constraints existing in the domain of interest. Since such constraints differ greatly for the various command and control domains noted in this report, it is very important that this variable be considered when interpreting the results of any research in terms of their applicability across domains. Such interpretations would be facilitated by a research effort which systematically manipulated time constraints to assess their effects on the various factors associated with the design of adaptive decision aids.

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